Design and optimization of a fin stabilizer using CFD codes and optimization algorithms

DESIGN AND OPTIMIZATION OF A FIN STABILIZER USING CFD CODES AND OPTIMIZATION ALGORITHM

Silverio DELLA ROSA [1], Marco MACERI [2], Ignazio Maria VIOLA [3], Simone BARTESAGHI [4],

[1] Aerospace Engineer, Yacht Designer and Consultant, Milan, Italy, silveriodellarosa@tiscalinet.it
[2] Senior Aerodynamicist at Pilatus Aircraft Ltd., Luzern, Switzerland, mac68@sunrise.ch
[3] Yacht Research Unit, The University of Auckland, New Zealand, im.viola@auckland.ac.nz
[4] Mechanical Engineer, Consultant, Milan, Italy, simone.bartesaghi@alice.it

ABSTRACT

In the present paper the design process of a stabilizer fin is presented. Different computational tools were adopted: a two-dimensional panel-code was used to design the two-dimensional airfoil candidates and an optimizer based on genetic algorithms was used to choose the optimum airfoil. A panel-code and a Navier-Stokes solver were successively adopted to verify the three-dimensional design. The two codes showed similar results at low angle of attacks, but differences enlarged when the angle of attack increased. The fins are also adopted as *zero-speed stabilizing fins*. The torque moment at the fin axis was computed for a constant angular velocity of the fin and zero boat speed. Finally, free surface computations modelling the boat free to sink and trim, and different fin trims, were performed and compared with experimental data.

1. INTRODUCTION

At the end of 2005, the Italian firm *C.M.C. Marine* charged the authors to design a set of fins for a new stabilizing system for ships and pleasure boats. *C.M.C. Marine* had developed a simulator tool able to compute the dynamics of the stabilizing system. In this paper, the design and the optimisation of the fins, and the computation of the fluid dynamic characteristics required by the stabilizing-system simulator are presented. The fins are built in composite materials on a Computer Numerical Control (CNC) milled moulds. This assured good surface and shape control, which motivated us in using advanced tools to evaluate the fluid dynamic performances. The design of stabilizing fin must take into account peculiar constrains, concerning the fin geometry and the flow field.

The stabilizing system must yield to production and accommodation requirements. It is often located in the engine room or where it doesn't interfere with the accommodation plan, not taking into account where the fins would be more efficient. The fin constrain of not increasing the yacht beam and draft, leads to a very short span compared to the fin area, therefore to a low aspect ratio. Structural and mechanical considerations lead to a large diameter rotation axle and hence, to a thick airfoil.

Finally, the fin design should take into account the flow field at the fin location, which involves the hull boundary layer, local wakes, interaction with waves, etc.

The research was focused on two aspects: design an optimised airfoil section, and design an efficient 3D fin plan-form.

2. DESIGN OF THE FIN PROFILE: AN EVOLUTIONARY STRATEGY

The target airfoil characteristics were large stall angle, best Cl- AoA slope, large nose radius, and tick trailing edge. A wide range of existing tabulated airfoils, for both turbulent and laminar conditions, were analysed with the 2D panel-code XFOIL. Some good candidates were found but none of them satisfied all the requirements listed above, particularly the large nose radius. Hence the code EDGA (Evolution Designs' Genetic Algorithm) was adopted to generate a new airfoil section with the best trade-off for the above requirements. The foil generated by the optimiser was tested against the best foils that were found in literature, and it showed better performance at the design conditions (Reynolds number $12 \cdot 10^6$; turbulent transition at 10% of the chord length).

EDGA (see Evolution Designs) is a code for designing and optimising airfoil, which is based on a real coded genetic algorithm. It produces highly-adapted optimised solutions with respect of

constraints and objectives (named *environmental pressure*). A genetic algorithm imitates the fundamental steps of the natural evolution of species, which replicates by mating. Genetic algorithms are proven to be efficient in searching spaces where many local extrema, in addition to the global one, might be present.
The search space is a hypercube whose dimensions are set by the number of the design parameters, which define the shape of an airfoil: nose radius, maximum thickness, curvature, etc. Advanced techniques, in order to enhance the search diversity, are implemented in the code, such as fitness sharing and SUS (Stochastic Universal Sampling), which avoid an evolution drifting to a local maximum/minimum, without exploring the whole search space. Archiving techniques prevent the loss of information of competitive solutions across the generation. The program allows multi-objective and multi-point optimisations, which allows one design and one off-design condition to be taken into account simultaneously into the optimisation runs.
The method, differently from most of the optimisation algorithms, doesn't need any "good enough" solution to start in order to produce an optimum solution.
This feature is paramount. In fact a designer may not always have access to airfoil databases. The selection of good candidates to be further optimised is a lengthy process which involves a very specific knowledge in this field. The optimisation engine of EDGA calls XFOIL (see Drela, 2001) to compute the fluid dynamic characteristics of each individual (i.e. airfoil) of a generation during the evolution.
When the fluid dynamic solver converges to a solution, the optimiser evaluates the fluid dynamic coefficients and the pressure distribution and computes the fitness of the individual. The selection process is based on each individual's fitness. The genes (i.e. design parameters) of the fittest solutions are more likely transmitted to the future generations. The interface of the program is extremely user-friendly and allows setting up a run in a short time. In one design session, a population of 20-wing sections is created and it evolves across 150 generations, which involves automatic generation, evaluation and selection of 3000 airfoils. A typical run takes a couple of hours on a modern PC.
The ease and the speed at which the solution can be generated and analysed allow different optimisation strategies to be adopted.

2.1.Run setup and results

Two objectives were specified in the optimisation process: the highest efficiency (i.e. lift/drag) at Angle of Attack AoA=3 degree, and the highest maximum lift. The search hypercube was constrained in order to generate only symmetric profiles. The turbulent transition was fixed at 10% of the chord length.
The optimisation engine quickly converged to the optima. Each objective is represented by a mathematical equation, which must be minimised in order to achieve to optima solutions.

3. 3D PLAN-FORM DESIGN

The CMC Marine simulator inputs are the basic fluid dynamic fin characteristics (e.g. the intercept and the slope of the Lift-AoA curve). The fin has very low aspect ratio and operates at high AoAs, moreover it works in strongly unsteady flow due to the ship movements.
Therefore, the usual finite wing theory and the standard simplified design methods are not adequate to evaluate the fin fluid dynamic characteristics. Plan-forms with different sweep angles and taper ratios were tested.
The inviscid code CMARC was adopted. It is a 3D potential-flow, which is based on low-order panel-method and incorporates boundary-layer displacement. The computations showed that at AoAs higher than 6 degree, the 3D cross flow due to the low aspect ratio leads to a significant lack of the lift.
The lift distribution along the span was improved adopting an endplate with delta shape at the fin tip. To reduce the drag due to the horseshoe vortex at the fin root, a large blending radius at the root and a double leading edge sweep angle were adopted.
Although it's common knowledge that panel codes do not model properly high AoAs, due to the large separated regions and the significant effect of the tip vortex involved, the code allowed the general flow field to be understood and several shapes at the root and at the tip to be tested. Successively, the Navier-Stokes (NS) code STAR-CCM+ v4.04.11 was adopted to evaluate the

selected designs. In fact, while the panel-code computes the hydrodynamic forces of a fin in few seconds, the NS code requires a few hours. Hence, the panel code is a useful design tool to evaluate a large amount of designs in a short time. The fluid dynamic characteristics of selected designs were evaluated with the NS code which allowed a deep understanding of the flow field at the root and at the tip. The computations led to a new design of the outer part of the fin, where the end plate is part of the same geometrical surface of the whole fin, achieving a smoother transition between the fin airfoil and the flat endplate.

3.1.Numerical setup

In the following, the computations performed with the two codes on the final geometry are presented. The Mean Aerodynamic Chord MAC of the stabilizing fin is 1.48 m and the surface S=1.2 m^2.

3.1.1. Panel-code

CMARC (see AeroLogic, 1995-2007) was used with the non-linear option, which incorporates boundary-layer displacement in the iterated solution. A mesh of about 4,000 panels was adopted to model the fin. The Code run 100 iterations for each AoA, with time step of 0.1 s and 3 inner iterations per step. This setup assured a good convergence of the lift and drag at the 3^{rd} significant digit.

3.1.2. Navier-Stokes code

Star-CCM+ v4.04.11 is a segregated finite-volume solver (see CD-adapco Group, 2009). The Reynolds Averaged Navier-Stokes (RANS) equations were solved for an incompressible fluid. The k-ε realizable (see Shih et al, 1995) turbulence model was used. Momentum, continuity, and turbulent equations were solved with a second order discretization scheme. Wall-functions were adopted to model the boundary layer.
The computational domain was a rectangular prism of 30 MAC in length, 10 MAC span-wise and 20 MAC wide. The fin was 10 MAC downstream the inlet surface. The fin surface was modelled with a non-slip condition, the boundary at the root and the opposite face of the domain prism were modelled with a slip condition (symmetry).
Modelling the root boundary layer generated on the hull surface requires a huge computational effort and hence, it was not modelled.
However, as shown below, it was modelled for the unsteady simulation performed to investigate the zero-speed condition. The velocity components were imposed at the inlet, and the turbulent kinetic energy k and the dissipation rate ε were set to zero. At the outlet, a uniform zero reference pressure was imposed (*pressure-outlet*).
Three-dimensional polyhedral elements were adopted for the whole domain ("figure 1"). Two-dimensional polyhedral cells, with a mean dimension of 0.01 MAC, modelled the fin surface. Sixteen prismatic layers modelled the boundary layer of the fin. The layers grew from the fin surface with a geometrical rate of 1.3. The height of the first layer was 0.00016 MAC in the wall-normal direction. The overall height of the prismatic region was 0.04 MAC. The size of the polyhedral cells grew from the prismatic region to the far-field region with a growth rate of 1.3, from a minimum linear size of 0.007 MAC to a maximum size of 1.5 MAC. Finally, 340,000 cells were adopted.
The lift and drag were monitored, and the computation was performed until the lift and drag oscillated around the same mean value for at least 50 cycles.

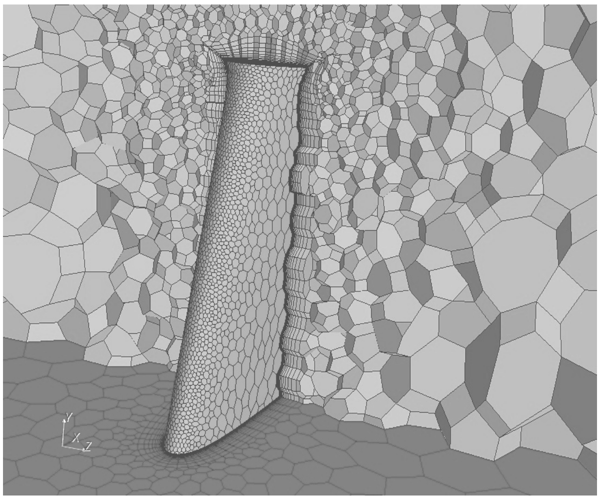

Figure 2. Prism layers and polyhedral cells around the fin.

3.2.Panel Code Versus NS Code Results

In the following, a comparison between lift and drag computed with the panel code and the NS code are presented. The flow fields computed by the two codes on the fin surface are in good agreement. Conversely, the flow field computed around the end-plate is significantly different.

Figure 2 shows the simulated streak lines for the two codes on the leeward side of the fin at AoA=20 degree. The streak lines computed by the two codes are almost straight on the fin surface, due to the large end-plate.

Conversely, they show significant differences on the end-plate surface. In fact, the panel-code estimates a smaller tip vortex than the NS code. As a consequence, the lift computed by the two codes is in a good agreement but the drag is significantly under-estimated by the panel code.

Figure 3 shows the wakes of the fin computed by the two codes. The tip vortex computed by the panel code rolls up significantly slower than the tip vortex computed by the NS code.

Figure 4 shows the drag computed with the two codes for a range of AoAs from 0 to 20 degree. The panel code computed a larger drag than the NS code, and the difference increases with the AoA.

Figure 5 shows the good agreement in the lift computed by the two codes. Most of the lift is due to the flow field on the fin, which is similarly computed by the two codes.

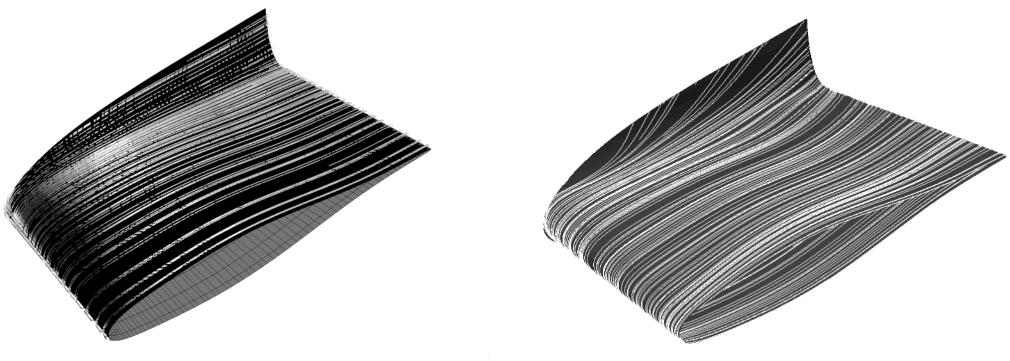

Figure 2. Streak lines computed with the panel-code (left) and the NS code (right), at AoA=20°.

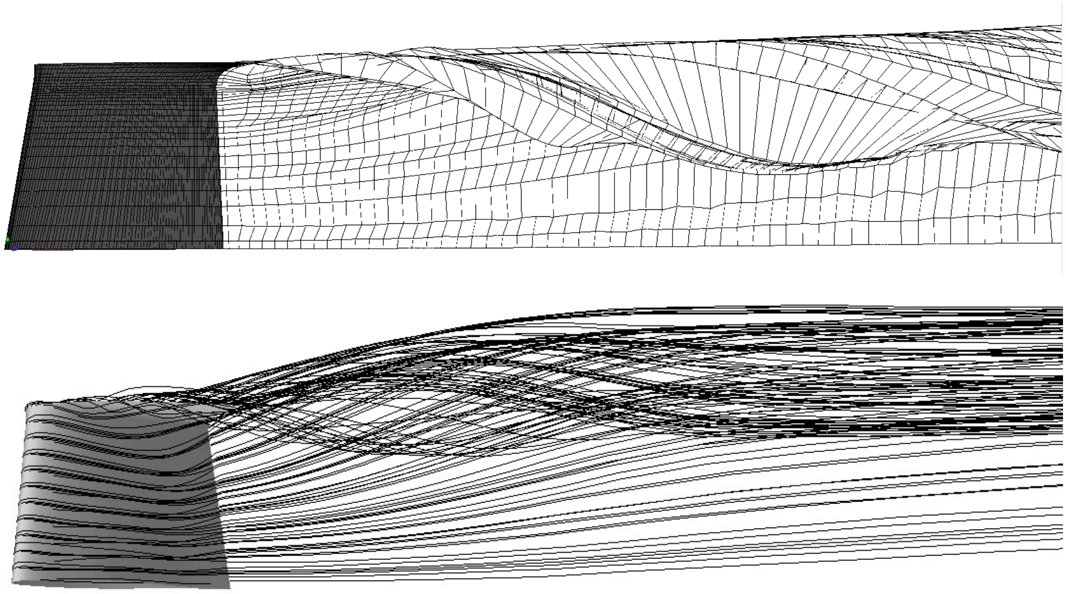

Figure 3. Stream lines computed with the panel code (top) and the NS code (bottom), at AoA=20°.

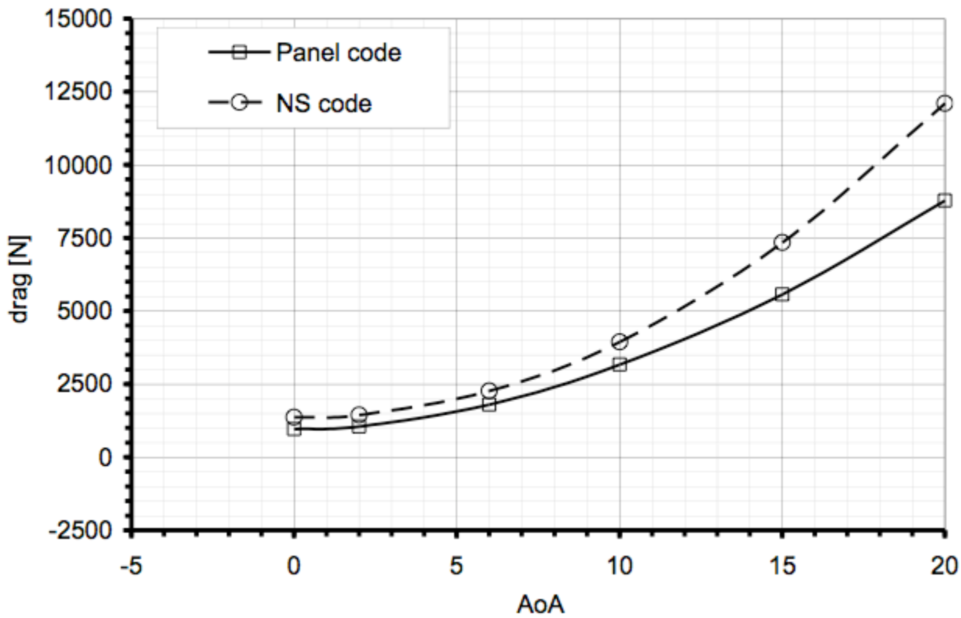

Figure 4. Drag computed by the panel code and the NS code versus the AoA.

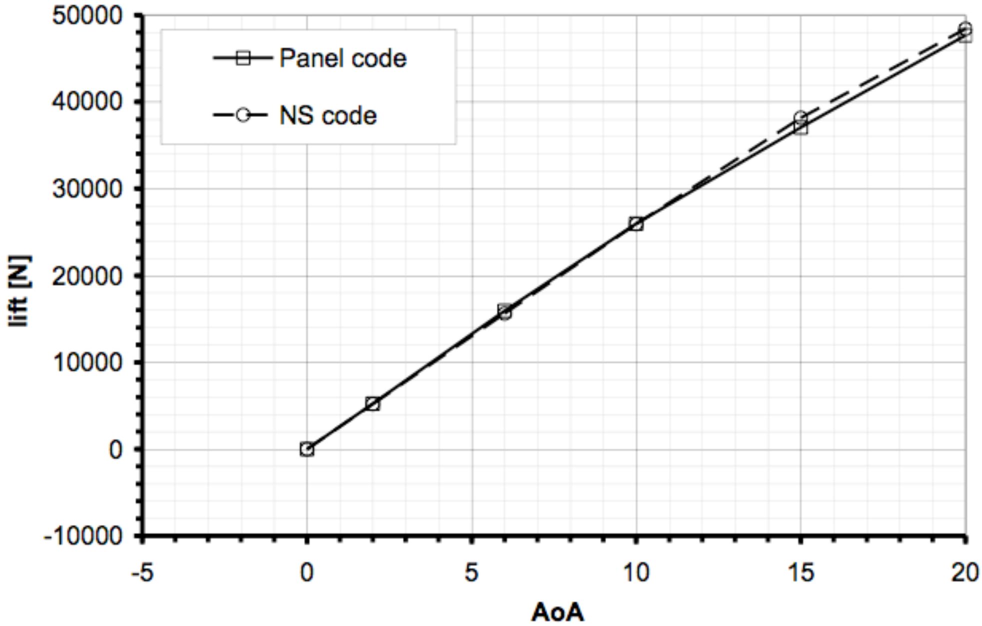

Figure 5. Lift computed by the panel code and the NS code versus the AoA.

4. STABILIZING FIN FOR SHIP AT ANCHOR

Special consideration should be adopted to design a fin which can provide stabilizing force even when the ship is at anchor or, generally, at null boat speed. The principle is intuitive: to react to a heeling moment due to waves, the fins rotate very fast generating a stabilizing moment, like a kayak paddle. Forces and moments acting on the fin have to be computed in order to design the hydraulic actuator. The NS code allowed forces and moments on stabilizing fin to be estimated.

4.1.Zero-speed simulation

Unsteady RANS simulations were performed to measure the torque moment at the fin axis for different defection angle d (Figure 6). The NS solver Star-CCM+ was used with the same setup described above. The first-order scheme was used for the time discretization.

The computational domain is a cylindrical prism with diameter 6.75 MAC and height 3.4 MAC.

Three-dimensional polyhedral elements were adopted for the whole domain. Two-dimensional polyhedral cells, with a mean dimension of 0.017 MAC, modelled the fin surface. Ten prismatic layers modelled the boundary layer of the fin. The layers grew from the fin surface with a geometrical rate of 1.3. The first layer was 0.00024 MAC in the wall-normal direction. The height of the prismatic region was 0.04 MAC. The largest polyhedron is 0.675 MAC. Finally, the total number of generated cells is 305.000.

The stabilizing fin was considered as rigid body which rotates in calm water. The rigid body motion was imposed. The fin rotated from d=0 to d=60 degree with a constant angular velocity of 11,67 rpm. The motion started and ended impulsively.

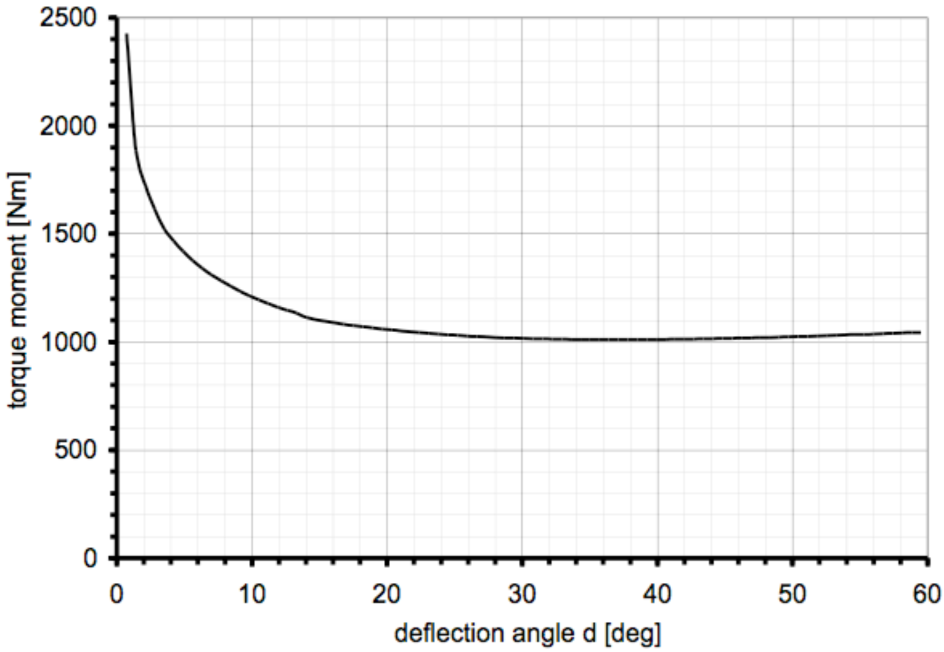

Figure 6. Torque moment versus deflection angle.

5. FIN-HULL INTERACTION

Finally, the resistance of the hull with and without the stabilizing fin in operating condition was computed. Three Unsteady RANS simulations were performed for the following geometries: the bare hull without the fins, the hull with the fins at deflection angle d=0 degree, the hull with the two fins at d=+15 and d=-15 degree respectively. A boat with a length at water line of LWL=29.26 m was chosen, sailing at the boat speed of V=13 knots, corresponding to a Froude number of Fr=0.395. The boat model was free to sink and trim. Hence sinkage, trim and resistance were computed. The free surface was computed with a Volume of Fluid (VOF) method: water and air are considered one fluid with variable properties, one of them is the fraction of air on water (i.e. VOF). An additional transport equation for the VOF is solved. The High Resolution Interface Capturing (HRIC) discretization scheme is used to ensure the sharpness of the interface. Hexahedral elements were adopted for the whole domain. The computational domains around the vessel extended for about 1 LWL in front of the bow, 2 LWL behind the stern, 0.3 LWL above the deck, 1.5 LWL below the skeg and to the two boat sides. The cell height of the wall-nearest cell was roughly 0.00054 MAC on the hull and 0.00020 MAC on the fin, resulting in a wall distance of y+=80 on the hull and y+=50 on the fin. Hence wall functions were adopted to model the boundary layer on both the hull and the fin.
In the simulations with the bare hull only and with the fins at zero deflection, only half vessel was modelled and a symmetry plane was set. About 590,000 and 880,000 hexahedral cells were adopted in the two simulations respectively. The full vessel was modelled when the two fins were trimmed at +/- 15 degree, requiring about 2,300,000 cells to be modelled.
Sink, trim and drag were monitored and the computation was run until all of them oscillated around the same mean value over the time needed for a particle of water to travel one computational domain length. Figure 7 shows the resistance computed for the three simulations divided by the experimental data. Towing tank data was achieved in model-scale and then it was scaled in full-scale. The bare hull simulation shows a good agreement with the experimental data, differences in the resistance is lower than 2%. When the fins are not deflected (d=0 degree), the added resistance due to the fin presence is small, whilst when the fins are deflected by d=+/-15 degree the resistance increased by roughly 15% compared to the zero-deflected fin condition. Figure 8 shows the streamline around the stabilizing fins at d=+/-15 degree. Figure 9 shows the free-surface elevation for the case with fins at d=+/-15 degree. The influence of the fins is shown by the asymmetric wave patterns. Contour lines show iso-value of

free-surface height, normalized by the draft (T=2.36 m). Contour lines are plotted every 0.1 normalized free-surface height.

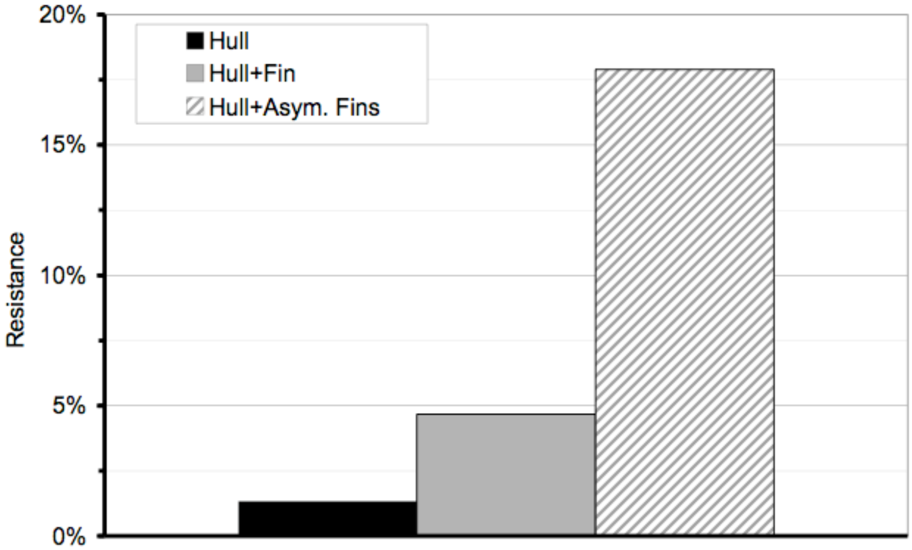

Figure 7. Hull resistance without fins, with fins at d=0 degree and d=+/-15 degree.

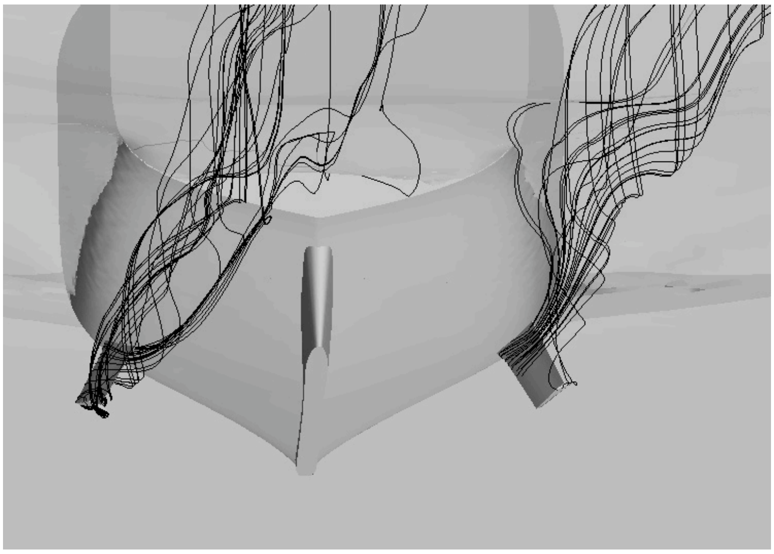

Figure 8. Streamlines around the stabilizing fins at d=+/-15 degree.

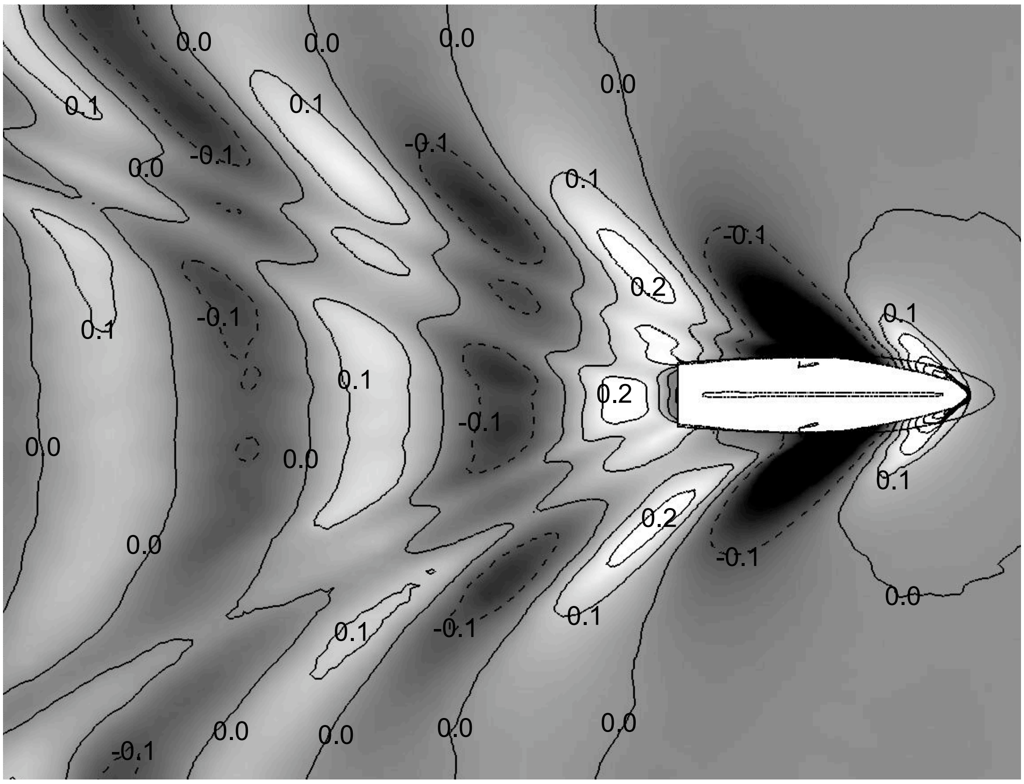

Figure 9. Free-surface normalized height at d=+/-15 degree.

6. CONCLUSION

The present work shows the design process of stabilizing fins with the aid of state-of-the-art design tools. An optimized two-dimensional airfoil was designed with a optimizer software based on genetic algorithms. The three-dimensional plan-form was firstly optimized with a panel-code with boundary layer integration. The small computational time required by the code allowed several plan-forms to be tested and a first roughly optimised plan-form to be selected. A finer optimisation was performed with a Navier-Stokes code, which required longer computational time but allowed to compute the fin fluid dynamics with higher accuracy. The comparison between the two codes on the optimized geometry showed good agreement in the lift but differences in the drag, increasing with the angle of attack.
The stabilizer fins were also adopted at zero boat speed. The torque moment at the fin axle was computed for a range of deflection angle between zero and 60 degree assuming an impulsive start and a constant angular velocity.
The increase in resistance due to the fin trim, sailing at the cruising boat speed, was computed. The bare hull resistance without fins were computed and compared with the towing tank data. The simulation computed the sink, trim and resistance showing very good agreement with the experimental data. Then the hull resistance with the fin at zero deflection angle was computed, showing a resistance increased of roughly 3%. Finally the two fins at deflection angle of +/-15 degree respectively were tested, showing a resistance increase by roughly 15%.
The present paper shows the capability of the state-of-the-art computational tools to aid the design process of marine appendages.

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